Theoretical Overview on Coherent Elastic Neutrino-Nucleus Scattering

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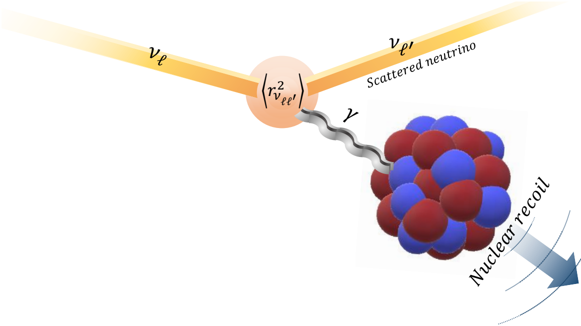
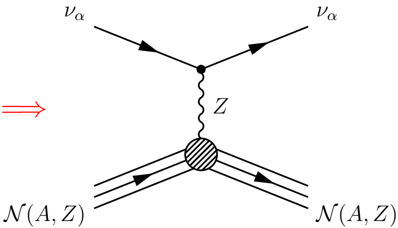


Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced “sevens”
- Neutral-Current (NC) interaction: $\boxed{\nu + \mathcal{N}(A,Z) \to \nu + \mathcal{N}(A,Z)}$

Standard Model $\Longrightarrow$



- The nucleus $\mathcal{N}(A,Z)$ recoils without any internal change of state!
- CEνNS was predicted in 1974! [Freedman, PRD 9 (1974) 1389]
- Experimental difficulty: low nuclear recoil kinetic energy $T \lesssim 10\,\text{keV}$
- CEνNS was observed for the first time 43 years later, in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($^{133}_{55}\text{Cs}_{78}$, $^{127}_{53}\text{I}_{74}$) [COHERENT, arXiv:1708.01294]
- Second observation in 2020 by the COHERENT experiment with a LAr detector ($^{40}_{18}\text{Ar}_{22}$) [COHERENT, arXiv:2003.10630]

CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\mathrm{CE}\nu NS}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W(Q^2)\right]^2$$

$$\boxed{|\vec{q}| = \sqrt{2\,M\,T}}$$

- Weak charge of the nucleus $\mathcal{N}$:

$$Q_W(Q^2) = g_V^n\,N\,F_N(|\vec{q}|) + g_V^p\,Z\,F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

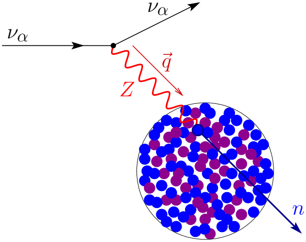
The neutron contribution is dominant! $\Longrightarrow \quad \dfrac{d\sigma_{\mathrm{CE}\nu NS}}{dT} \propto N^2$

[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto N \Longrightarrow \sigma_{\mathrm{CE}\nu NS}/\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto N$

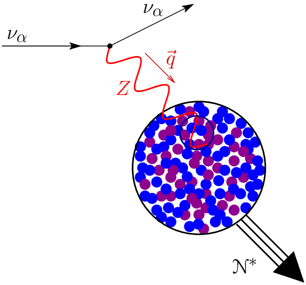
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

Neutrino-Nucleus Scattering



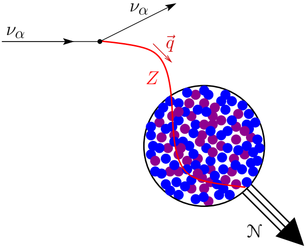
Inelastic Incoherent

$\lambda_Z \ll R$



Elastic Incoherent

$\lambda_Z \lesssim R$



Elastic Coherent

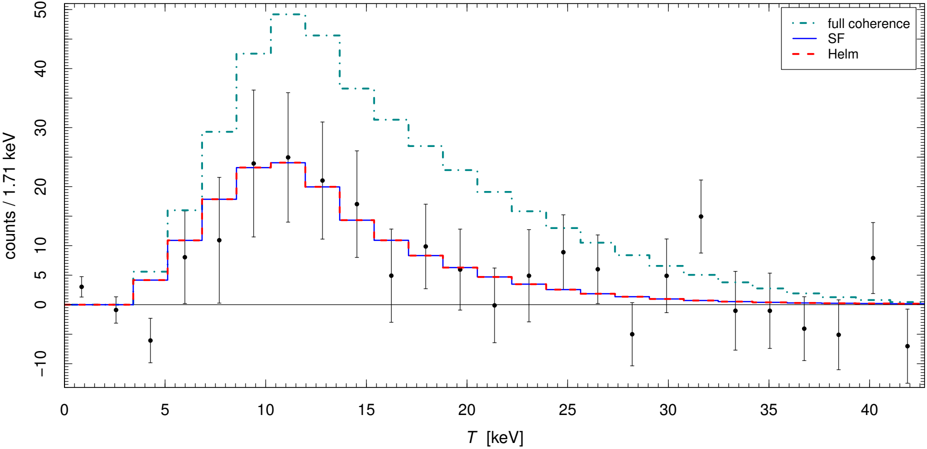
$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|} \quad \Longrightarrow \quad \text{CE}\nu\text{NS for } |\vec{q}|\, R \lesssim \hbar$$

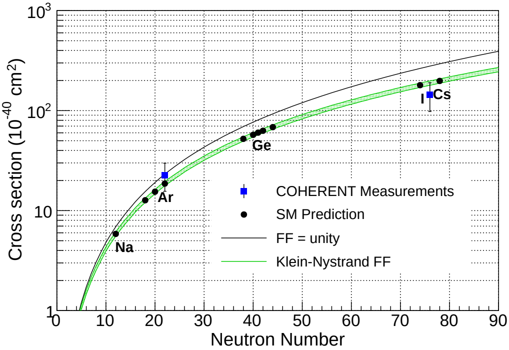
$$\boxed{|\vec{q}|\, R \lesssim 1} \quad \leftarrow \quad \text{Natural Units}$$

- In the COHERENT experiment the scattering is not completely coherent

$$\text{CsI:}\ \left\{ \begin{array}{l} |\vec{q}| \sim 30 - 80\,\text{MeV} \sim 0.1 - 0.4\,\text{fm}^{-1} \\ R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm} \end{array} \right\} \Longrightarrow |\vec{q}|R \sim 0.5 - 2$$



[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]



[COHERENT, arXiv:2003.10630]

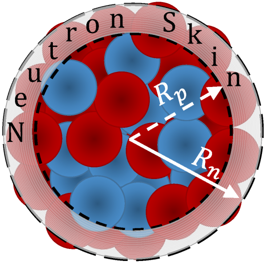
- Partial coherency is described by the nuclear neutron form factor $F_N(|\vec{q}|)$
- Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}}\, \rho_N(r)\, d^3r$$

- Measurable parameter: the radius R_n of the nuclear neutron distribution

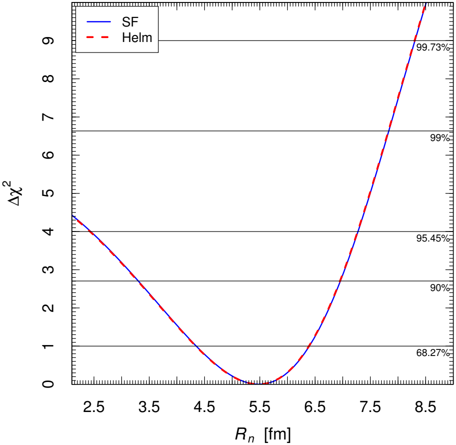
The Nuclear Proton and Neutron Distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements.
  But they are more difficult.



- Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering:
  $R_n(^{208}\mathrm{Pb}) = 5.78^{+0.16}_{-0.18}\,\mathrm{fm}$ [PREX, arXiv:1201.2568]
  Larger than $R_p(^{208}\mathrm{Pb}) = 5.5028 \pm 0.0013\,\mathrm{fm} \Longrightarrow$ Neutron Skin

$$\boxed{\Delta R_{np} = R_n - R_p}$$



- Fit of the 2017 COHERENT CsI data:

$$\boxed{R_n(\mathrm{CsI}) = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}}$$

[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]

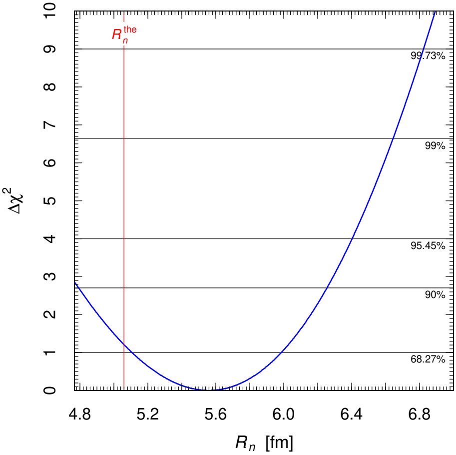
- $R_n(\mathrm{CsI}) \simeq R_n(^{133}\mathrm{Cs}) \simeq R_n(^{127}\mathrm{I})$
- First determination of R_n with neutrino-nucleus scattering.
- Best fit larger than

$$R_p(^{133}\mathrm{Cs}) = 4.821 \pm 0.005\ \mathrm{fm}$$

$$R_p(^{127}\mathrm{I}) = 4.766 \pm 0.008\ \mathrm{fm}$$

Indicates a sizable neutron skin

[see also: Papoulias, Kosmas, Sahu, Kota, Hota, arXiv:1903.03722; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Coloma, Esteban,Gonzalez-Garcia, Menendez, arXiv:2006.08624]



- With new 2020 COHERENT CsI data: [Pershey @ Magnificent CEνNS 2020]

$$\boxed{R_n(\text{CsI}) = 5.55 \pm 0.44\,\text{fm}}$$

[Cadeddu et al, arXiv:2102.06153]

- Neutron skin:

$$\Delta R_{np}(\text{CsI}) = 0.76 \pm 0.44\,\text{fm}$$

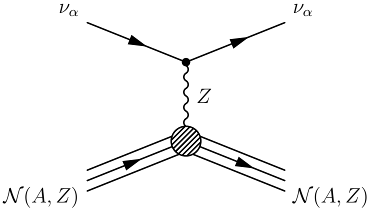
- Predictions of nuclear models:

$$\Delta R_{np}(\text{CsI}) \approx 0.1 - 0.3\,\text{fm}$$

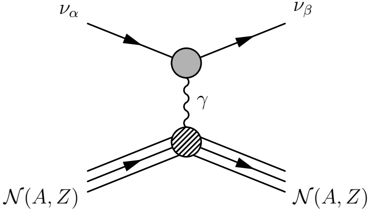
- A large neutron skin has important implications for:
  - Nuclear physics: a larger pressure of neutrons
  - Astrophysics: a larger size of neutron stars

SM and BSM CEνNS Neutrino Interactions

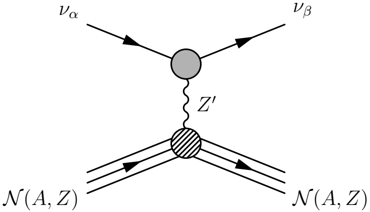
Standard Model NC



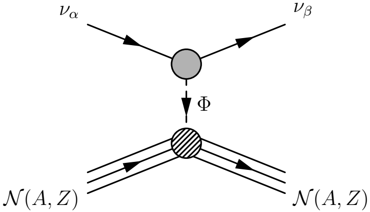
Electromagnetic Interactions



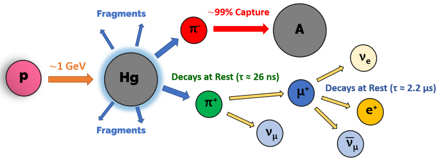
BSM Vector Mediator

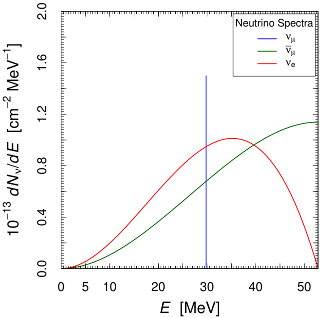


BSM Scalar Mediator



COHERENT Stopped-Pion Neutrino Source





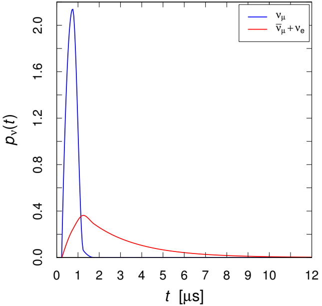
- **Prompt monochromatic ν_μ** from stopped pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu$$

- **Delayed $\bar{\nu}_\mu$** and ν_e from the subsequent muon decays:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

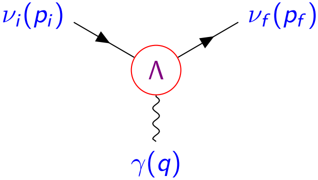
- Allows to probe SM and BSM neutral current ν_e and ν_μ interactions, that are distinguished by different energy and time distributions



Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge (F_Q), anapole (F_A), magnetic (F_M), electric (F_E)

$q^2 = 0 \quad \Longrightarrow \quad q \quad a \quad \mu \quad \varepsilon$

helicity-conserving (q, a)

helicity-flipping (μ, ε)

Electromagnetic Vertex Function

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[F_Q(q^2) + F_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors:

charge   anapole   magnetic   electric

$$q^2 = 0 \quad \Longrightarrow \quad q \qquad a \qquad \mu \qquad \varepsilon$$

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

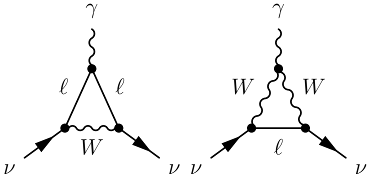
  no diagonal charges and electric and magnetic moments in the mass basis
- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1$ ⇒ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

[see the review CG, Studenikin, arXiv:1403.6344

and the update in Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606]

- Neutrino charge radii contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left\{\left[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|) + \left(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} - \frac{2}{3} m_W^2 \sin^2\vartheta_W \langle r^2_{\nu_{\ell\ell}}\rangle\right) Z F_Z(|\vec{q}|)\right]^2 + \frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2\right\}$$

- In the Standard Model there are only diagonal charge radii $\langle r^2_{\nu_\ell}\rangle \equiv \langle r^2_{\nu_{\ell\ell}}\rangle$ because lepton numbers are conserved.

- Diagonal charge radii generate the coherent shifts

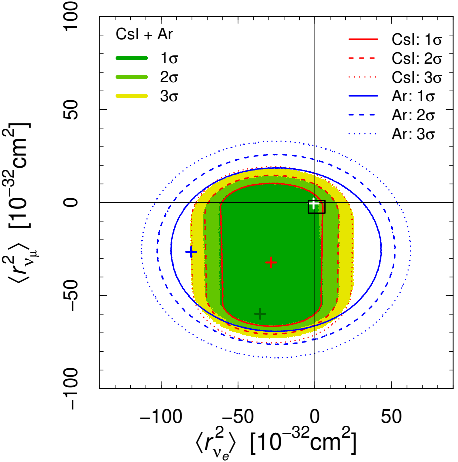
$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

$$\frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2 \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \sum_{\ell' \neq \ell} \nu_{\ell' \neq \ell} + \mathcal{N}$$

[Kouzakov, Studenikin, arXiv:1703.00401]

COHERENT constraints on neutrino charge radii



$$|\langle r^2_{\nu_{e\mu}} \rangle| < 36 \times 10^{-32}\,\text{cm}^2$$
$$|\langle r^2_{\nu_{e\tau}} \rangle| < 50 \times 10^{-32}\,\text{cm}^2 \qquad (3\sigma)$$
$$|\langle r^2_{\nu_{\mu\tau}} \rangle| < 44 \times 10^{-32}\,\text{cm}^2$$

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]

Effective charge radii
in the flavor basis:

$$\langle r^2_{\nu_{\ell\ell'}} \rangle = \sum_{j,k} U^*_{\ell j} U_{\ell' k} \langle r^2_{\nu_{jk}} \rangle$$

[see also: Papoulias, Kosmas, arXiv:1711.09773; Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045; Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

Neutrino Electric Charges

- Neutrinos can be millicharged particles in theories beyond the Standard Model.

- Neutrino charge contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left\{\left[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|) + \left(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} + \frac{2m_W^2 \sin^2\vartheta_W}{MT}\, q_{\nu_{\ell\ell}}\right) Z F_Z(|\vec{q}|)\right]^2 + \frac{4m_W^4 \sin^4\vartheta_W}{M^2 T^2}\, Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |q_{\nu_{\ell\ell'}}|^2\right\}$$

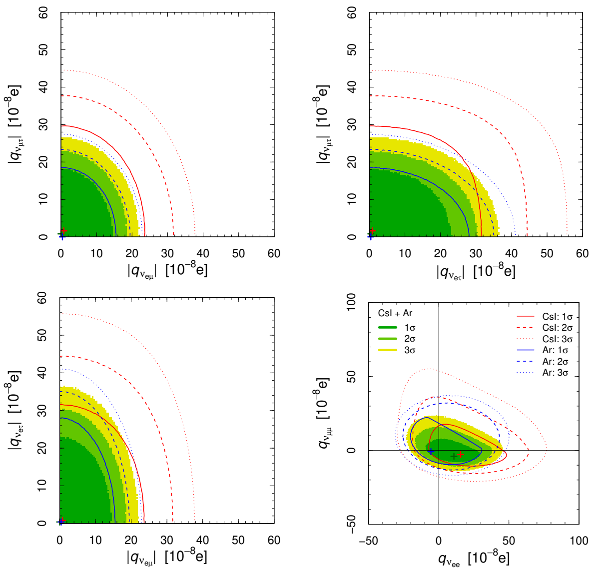
- $q_{\bar{\nu}_{\ell\ell'}} = -q_{\nu_{\ell\ell'}}$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.

Limits on neutrino millicharges

Limit	Method	Reference
$\lvert q_{\nu_e}\rvert \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999)
$\lvert q_{\nu_e}\rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko et al (2006)
$\lvert q_{\nu_e}\rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)
$\lvert q_{\nu_e}\rvert \lesssim 1.0 \times 10^{-12}\, e$	Nuclear reactors	Chen et al (2014)
$\lvert q_{\nu_\mu}\rvert \lesssim 3 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_{\mu\tau}}\rvert \lesssim 2 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_\mu}\rvert \lesssim 3 \times 10^{-9}\, e$	LSND	Das et al (2020)
$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-6}\, e$	DONUT	Das et al (2020)
$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu et al (1993)
$\lvert q_{\nu}\rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson et al (1991)
$\lvert q_{\nu}\rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 4 \times 10^{-35}\, e$	Neutrality of Universe	Caprini, Ferreira (2003)

COHERENT constraints on neutrino millicharges

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]



- Effective charges in the flavor basis:

$$q_{\nu_{\ell\ell'}} = \sum_{j,k} U_{\ell j}^{*} U_{\ell' k}\, q_{\nu_{jk}}$$

- The bounds on the charges involving the electron neutrino flavor

  $q_{\nu_{ee}}$ $q_{\nu_{e\mu}}$ $q_{\nu_{e\tau}}$

  are not competitive with respect to those obtained in reactor neutrino experiments, that are at the level of $10^{-12}\,e$ in neutrino-electron elastic scattering experiments.

- The bounds on

  $q_{\nu_{\mu\mu}}$ $q_{\nu_{\mu\tau}}$

  are the first ones obtained from laboratory data.

[future prospects: Parada, arXiv:1907.04942]

Neutrino Magnetic and Electric Moments

- Extended Standard Model with Dirac massive neutrinos ($\Delta L = 0$):

$$\mu^{\mathrm{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left(\frac{m_k}{\mathrm{eV}} \right) \qquad \varepsilon^{\mathrm{D}}_{kk} = 0$$

$$\left. \begin{matrix} \mu^{\mathrm{D}}_{kj} \\ i\varepsilon^{\mathrm{D}}_{kj} \end{matrix} \right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left(\frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell = e,\mu,\tau} U^*_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, hep-ph/0305206]

- Extended Standard Model with Majorana massive neutrinos ($|\Delta L| = 2$):

$$\mu^{\mathrm{M}}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k + m_j) \sum_{\ell = e,\mu,\tau} \mathrm{Im}\left[U^*_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

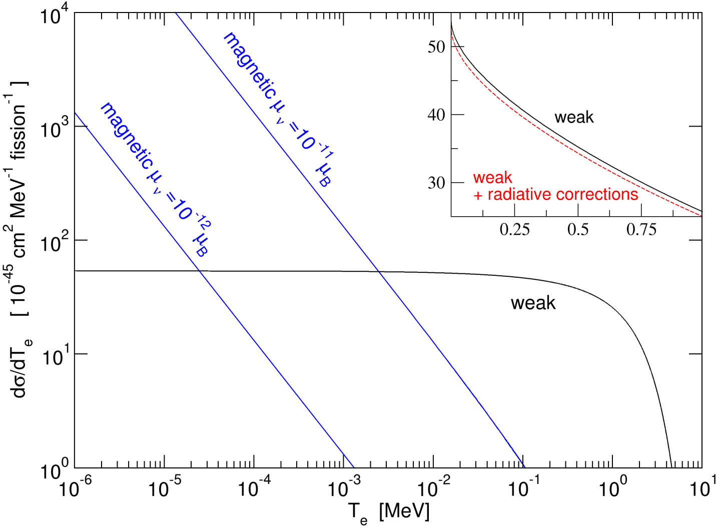
$$\varepsilon^{\mathrm{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell = e,\mu,\tau} \mathrm{Re}\left[U^*_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\mathrm{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_{\mathrm{B}}}\right)^2$$



[Balantekin, Vassh, arXiv:1312.6858]

Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review CG, Studenikin, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery ⇒ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

- Neutrino magnetic (and electric) moment contributions to CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_{\text{F}}^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)\right]^2$$

$$+\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|)\frac{\mu_{\nu_\ell}^2}{\mu_{\text{B}}^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- Effective magnetic moment of flavor neutrinos:

$$\mu_{\nu_\ell}^2 = \sum_j \left|\sum_k U_{\ell k}^* \left(\mu_{jk} - i\varepsilon_{jk}\right)\right|^2$$

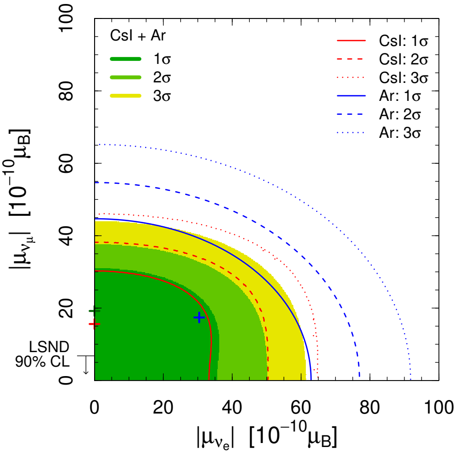
[Grimus, Stockinger, hep-ph/9708279;
Beacom, Vogel, hep-ph/9907383;
CG, Studenikin, arXiv:1403.6344]

- Neglecting the electric moments:

$$\mu_{\nu_\ell}^2 = \sum_{i,j} U_{\ell i}\,(\mu^2)_{ij}\,U_{\ell j}^* \quad \text{with} \quad (\mu^2)_{ij} = \sum_k \mu_{ik}\mu_{kj}$$

COHERENT constraints on ν magnetic moments

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]



- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11}\,\mu_B \quad (90\%\ \text{CL})$$

[GEMMA, AHEP 2012 (2012) 350150]

- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

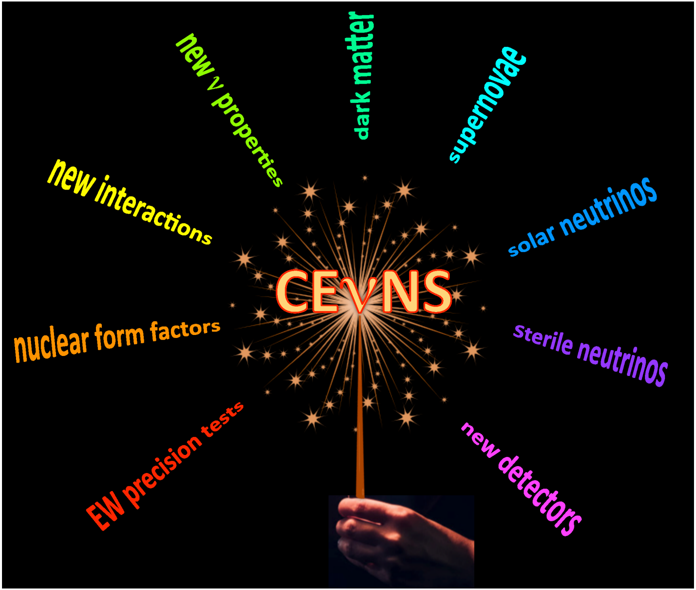
$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}\,\mu_B \quad (90\%\ \text{CL})$$

[LSND, hep-ex/0101039]

[see also: Papoulias, Kosmas, arXiv:1711.09773; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045; Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

[future prospects: Miranda, Papoulias, Tortola, Valle, arXiv:1905.03750]

Conclusions



[E. Lisi, Neutrino 2018]